On Applying Network Coding in Network Assisted Device-to-Device Communications

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***Abstract*—Device-to-device (D2D) communication has been shown to increase the spectrum and energy efficiency of local communication sessions in cellular networks. On the other hand, physical layer network coding (NWC) at a cellular base station — which can be employed without D2D functionality — can also improve the efficiency of a cellular network that carries local traffic. In this paper we study the joint application of D2D and NWC technologies with the purpose of further improving the performance of cellular networks that employ either D2D or NWC alone. We find that the joint D2D and NWC scheme yields additional gains, provided that the network exercises proper mode selection (MS) and resource allocation. Specifically, a cellular network that supports *both* D2D and NWC can achieve higher spectral and energy efficiency than a network that employs only one of these schemes.**

I. INTRODUCTION

Device-to-device (D2D) communication in cellular spectrum supported by a cellular network enables direct communication between pieces of user equipment (UE) [1], [2]. The main purpose of incorporating D2D communication in cellular networks is to exploit the proximity of UEs when engaged in local communication sessions such as social networking, media sharing, or proximity-based services [3].

In the presence of such proximate communication opportunities, D2D has been shown to harvest not only the proximity gain in terms of improved link budget, but also the so called reuse and hop gains [2], [4], [5], [6], [7]. A key technology component of D2D is mode selection (MS), which selects the cellular or direct communication mode for a D2D pair based on factors such as the current resource situation, traffic load, and interference level [7]. Recognizing the potential of D2D, the research community has proposed efficient scheduling, resource allocation, and power control algorithms that help realize the gains of local communications, while at the same time protecting the cellular layer from interference caused by local traffic [8]. These promising results have triggered standards bodies such as the 3rd Generation Partnership Project (3GPP) to study the possibilities of introducing D2D in future releases of Long Term Evolution (LTE) networks [9].

Along another line of research, it has been observed that physical layer network coding (NWC) improves the spectrum efficiency by facilitating resource reuse by multiple transmissions and taking advantage of advanced signal processing techniques [10], [11]. Despite the obvious differences between cellular network-integrated D2D and NWC technologies, both aim to improve spectral efficiency and increase network capacity by enabling tighter reuse of resources. As a related study has noted, under some assumptions, NWC can be used to further enhance the efficiency of D2D communication by combining cellular and direct transmission in integrated D2D and cellular networks [12]. On the other hand, the joint application of D2D and NWC may be costly in terms of UE capabilities, measurement reports, and signaling, while it is not clear whether an integrated D2D-NWC-based solution for dealing with local traffic results in additional gains over a system that uses either D2D or NWC alone. Therefore, we aim to answer the following questions:

- Does NWC provide gains in integrated D2D-cellular networks?
- Does D2D provide gains in a cellular network employing NWC?

To this end, we structure the paper as follows. The next section discusses the possible transmission modes in an integrated D2D-cellular network that can employ different forms of NWC. Section III develops a system model and discusses the key performance aspects. Next, in Section IV we propose mode selection and resource allocation schemes applicable in the integrated D2D-NWC environment. Section V presents numerical results and Section VI concludes the paper.

II. EMPLOYING D2D AND NWC TO SUPPORT LOCAL TRAFFIC

Consider Figure 1 for a comparison of the operation of D2D and NWC in the presence of local traffic. In this scenario, UE1 and UE2 are served by the same base station (eNB) and engage in a local communication session. D2D technology offers the possibility of direct communication, in which case a bidirectional exchange of signals x_1 and x_2 require two orthogonal resources. [1] For example, assuming time division duplexing (TDD), using D2D, x_1 and x_2 can be sent in subsequent time slots (TS-1 and TS-2).

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[1] In this paper we do not consider the application of full-duplex communication.

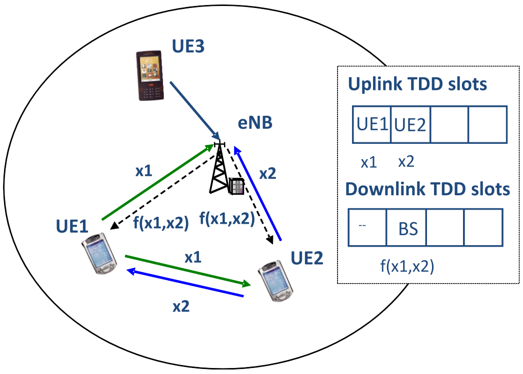

Fig. 1. D2D and NWC technologies integrated in a cellular network, here exemplified by the 3-TS NWC scheme. In uplink TS-1, UE1 transmits x_1. In uplink TS-2, UE2 transmits x_2 and finally in downlink TS-3, the eNB transmits the network coded data $f(x_1, x_2)$.

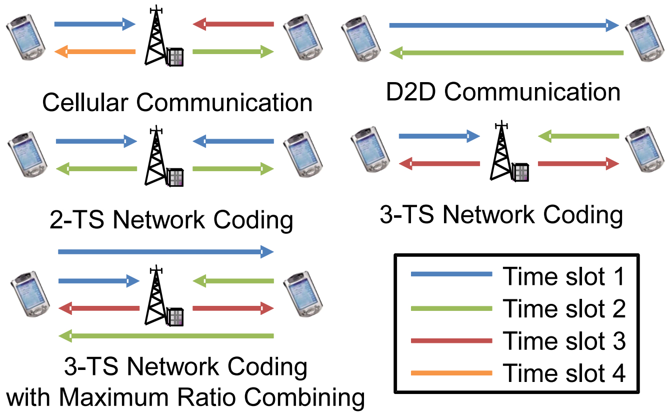

Fig. 2. An overview of the available transmission modes for local communications. The fifth transmission mode (3-TS NWC with maximum ratio combining) integrates D2D and NWC in a joint scheme. Note that cellular communication corresponds to the 4-TS scheme.

Alternatively, in a cellular network employing physical layer NWC (without D2D communication), two time slots can support the exchange of x_1 and x_2. In this case, UE1 and UE2 transmit on the *same* resource (TS-1), while the eNB uses TS-2 to transmit the NWC data $f(x_1, x_2)$ to UE1 and UE2 simultaneously [13], [10], [11]. UE1 and UE2 receive $f(x_1, x_2)$ and decode x_2 and x_1, respectively.

As an alternative to the physical layer (also called 2 time slot, 2-TS) network coding scheme, the 3-TS NWC scheme uses different resources for transmitting x_1 and x_2 to the eNB, while the eNB uses TS-3 to transmit $f(x_1, x_2)$. In this 3-TS scheme, the joint application of D2D and NWC becomes possible, as depicted in Figure 1. In the joint mode, UE2 receives both the direct transmission from UE1 (in uplink TS-1) and the network coded transmission from the eNB (in DL TS-2). UE2 can then employ signal processing (for example, maximum ratio combining with maximum likelihood detection, as in [12]) to combine the received signals such that the bit error rate is improved over the 2-TS scheme without D2D transmission and reception.

Figure 2 summarizes the possible transmission modes enabled for local traffic by cellular, D2D, and NWC technologies. Note that, in Figure 2, the traditional cellular transmissions (without D2D and NWC) of x_1 and x_2 correspond to a 4-TS scheme [10], since both x_1 and x_2 must be transmitted through the eNB using an uplink and a downlink resource.

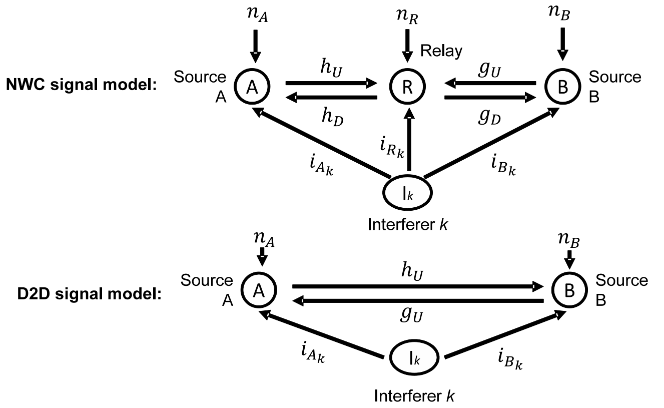

Fig. 3. Signal models for NWC and D2D transmissions. Source A transmits signal x_A with power P_A while source B transmits signal x_B with power P_B. NWC transmission involves a relay node (in this case is the base station) while D2D transmission does not. The relay transmits with power P_R.

In this paper, we focus on three transmission schemes: cellular communication (4-TS scheme), physical layer network coding (2-TS network coding), and D2D communications.

III. PERFORMANCE ASPECTS

To gain insights into the advantages of the available local communication schemes (Figure 2), including D2D or NWC alone or in combination, we consider a simplified signal model and use a realistic system simulator to analyze the system performance. We evaluate the end-to-end signal-to-interference-and-noise ratio (SINR), total transmit power in the bidirectional transmission ($P_A + P_B + P_R$), and spectral efficiency (a logarithmic function of the SINR divided by the number of required time slots).

A. Signal Model

The signal models applicable for NWC-based and D2D-based transmissions are shown by Figure 3, where h and g denote the complex channel coefficients and n denotes additive Gaussian noise.

1) Network Coding: Source A and source B would like to send their information to each other. When NWC is employed, the communication is done through a relay which forwards the information from source A to source B and vice versa. In a local communication session, it is assumed that sources A and B are UEs while the relay node is the base station (eNB).

Each node receives additional Gaussian noise $n_A, n_B, n_R \sim \mathcal{CN}(0, \sigma^2)$. Each node also experiences interference from other transmitters utilizing the same resource.

Notations $h_U, g_U, h_D, g_D, i_{A_k}, i_{R_k}$ and i_{B_k} represent channel gains. The channels are assumed to be asymmetric, i.e. uplink and downlink channels can have different channel gains to support, for example, frequency divsion duplex (FDD) networks and to allow time varying channels in time division duplex (TDD) systems.

2) D2D Communication: In D2D communications, the sources communicate with each other through direct links. There is no relay node assisting the information exchange.

B. SINR Analysis

The SINR analysis for the network coding schemes is based on [10]. The notations x_A, x_B, and x_{I_k} represent data symbols transmitted by source A, source B, and interferer k respectively. We assume that $|x_A|^2 = |x_B|^2 = |x_{I_k}|^2 = 1$. The transmit power levels of source A, source B, the relay, and interferer k are written as P_A, P_B, P_R, and P_{I_k}. Furthermore, let us define $P_{I_k}^{(t)}$, $i_{R_k}^{(t)}$, $i_{A_k}^{(t)}$, $i_{B_k}^{(t)}$, and $x_{i_k}^{(t)}$ as the transmit power, channel gains, and data symbols associated to interferer k in time slot t.

Note that the notion of SINR used in this context is different from the traditional single-link SINR. Specifically, we use *end-to-end* SINR which accounts for both source-to-relay and relay-to-destination SINRs to better characterize the different transmission schemes. The expressions of the examined transmission schemes listed in Figure 2 are given in the following section, while the derivations are given in the Appendix. Note that we only present the end-to-end SINR at source A. End-to-end SINR at source B is derived in the same manner and is statistically equivalent.

1) Two-Time Slot (2-TS) Network Coding: For the 2-TS NWC scheme, the end-to-end SINR at source A is calculated as follows.

$$\gamma_A = \frac{G^2 P_R |h_D|^2 P_B |g_U|^2}{G^2 P_R |h_D|^2 \psi_2 + \sum\limits_k P_{I_k}^{(2)} |i_{A_k}^{(2)}|^2 + \sigma^2}, \tag{1}$$

$$\psi_2 = \left(\sum_k P_{I_k}^{(1)} |i_{R_k}^{(1)}|^2 + \sigma^2 \right); \tag{2}$$

where G is the gain by which the received signals from the sources are amplified at the relay. For 2-TS network coding, G is given by

$$G = \sqrt{\frac{1}{P_A |h_U|^2 + P_B |g_U|^2 + \sigma^2}}.$$

Note that similarly to the model used in [11], the G normalization factor only depends on the transmit power P_A and P_B, but not on the P_{I_k} interference power levels (see also the signal model defined by (7) in the Appendix).

2) Four-Time Slot (4-TS) Scheme: In the 4-TS scheme, the relay gain G_A is given as follows.

$$G_A = \sqrt{\frac{1}{P_B |g_U|^2 + \sigma^2}}.$$

The end-to-end SINR at source A is calculated as follows.

$$\gamma_A = \frac{G_A^2 P_R |h_D|^2 P_B |g_U|^2}{G_A^2 P_R |h_D|^2 \psi_{4,A} + \sum\limits_k P_{I_k}^{(4)} |i_{A_k}^{(4)}|^2 + \sigma^2}, \tag{3}$$

$$\psi_{4,A} = \left(\sum_k P_{I_k}^{(3)} |i_{R_k}^{(3)}|^2 + \sigma^2 \right). \tag{4}$$

3) D2D Communication: This transmission scheme is a bidirectional direct transmission, without relay. It is assumed that a transmission in one direction requires one time slot, which results in two time slots needed in total. The received signal at source A is given as follows.

$$y_A = \underbrace{\sqrt{P_B} g_u x_B}_{\text{desired signal}} + \left(\sum_k \sqrt{P_{I_k}^{(2)}} i_{A_k}^{(2)} x_{i_k}^{(2)} \right) + n_A.$$

Taking the ratio of desired signal's power over interference and noise power, SINR value at sources A is calculated as follows.

$$\gamma_A = \frac{P_B |g_U|^2}{\left(\sum\limits_k P_{I_k}^{(2)} |i_{A_k}^{(2)}|^2 \right) + \sigma^2}.$$

IV. PROPOSED RESOURCE ALLOCATION AND MODE SELECTION ALGORITHMS

A. Resource Allocation

The resource allocation algorithm proposed in this paper makes use of resource utilization counters in conjunction with a simple random allocation. The idea is to allocate the resources which are least used, avoiding the case of a high number of links sharing the same resource, hence the term *balanced*. We assume that after a series of signalling, the eNB has knowledge of which UL and DL resources are used by all UEs within its coverage area. Let us define UL and DL utilization vectors $\rho_{\mathbf{U}}$ and $\rho_{\mathbf{D}}$, and denote $\rho_U(i)$ as the utilization counter of UL resource i and $\rho_D(j)$ as the utilization counter of DL resource j. For each communicating UE pair, UE-A and UE-B, the eNB needs to pick two UL resources and two DL resources (let us denote them as *U1*, *U2*, *D1*, and *D2*) which will be the candidates of allocated resources for a two-way communication between UE-A and UE-B.

The eNB does the following:

1) Pick the first UL resource, *U1*, by picking an UL resource i randomly out of the resources for which $\rho_U(i) = \min(\rho_{\mathbf{U}})$.
2) Increment $\rho_U(i)$, $\rho_U(i) \leftarrow \rho_U(i) + 1$.
3) Pick the second UL resource, *U2*, by picking an UL resource i randomly out of the resources for which $\rho_U(i) = \min(\rho_{\mathbf{U}})$.
4) Increment $\rho_U(i)$, $\rho_U(i) \leftarrow \rho_U(i) + 1$.
5) Pick the first DL resource, *D1*, by picking a DL resource j randomly out of the resources for which $\rho_D(j) = \min(\rho_{\mathbf{D}})$.
6) Increment $\rho_D(j)$, $\rho_D(j) \leftarrow \rho_D(j) + 1$.
7) Pick the second DL resource, *D2*, by picking a DL resource j randomly out of the resources for which $\rho_D(j) = \min(\rho_{\mathbf{D}})$.

8) Increment $\rho_D(j)$, $\rho_D(j) \leftarrow \rho_D(j) + 1$.

At the end of balanced random allocation process, four resources (*U1*, *U2*, *D1*, and *D2*) are picked and the resource utilization counters are updated.

B. Mode Selection (MS)

Based on Figure 2 and the signal model, we expect a trade-off between the number of used resources, invested transmission energy, and the resulting SINR levels, and thereby the achieved spectral and energy efficiencies. Therefore, for an integrated D2D-NWC-cellular network, we developed two MS algorithms that aim to maximize the achieved SINR (**MS-NWC 1**) and the spectral efficiency (**MS-NWC 2**), respectively.

In our proposed mode selection, the eNB makes a prediction of end-to-end SINR for the investigated transmission modes based on the channel knowledge, selected resources, and assumptions on eNB and UE transmit power. At this prediction stage, all UEs are assumed to transmit with a constant power of P, because we assume that the resource allocation and mode selection take place before power control is performed. For the eNB to be able to make an end-to-end SINR prediction, it employs a mathematical model and computation technique that is characteristic to the specific transmission mode, as described in Section III-B.

1) MS-NWC 1 (SINR-Maximizing Mode Selection): The eNB selects the mode that has the highest predicted end-to-end SINR.

2) MS-NWC 2 (Spectral Efficiency-Maximizing Mode Selection): The eNB selects the mode that has the highest predicted spectral efficiency, $\hat{S}$. This prediction takes the end-to-end SINR prediction ($\hat{\gamma}_{mode}$) as well as the number of consumed resources (τ_{mode}) into account.

$$\hat{S}_{mode} = \frac{\log_2\left(1 + \hat{\gamma}_{mode}\right)}{\tau_{mode}} \tag{5}$$

In (5), τ_{mode} is equal to 4 for cellular mode, 3 for classical network coding and network coding with MRC modes, and 2 for physical layer network coding and D2D modes.

V. NUMERICAL RESULTS

A. Simulation Setup

We simulate a multicell network and build statistics using Monte Carlo simulation method. In each iteration, a cellular system is generated with a fixed number of cells, a fixed number of locally communicating UE pairs per cell, and a fixed number of radio resources per cell. UEs are dropped randomly within the cell with uniform distribution. Additionally, we consider both low traffic and high traffic scenarios. Simulation parameters are listed in Table I.

We assume that the system employs LTE open-loop fractional path loss compensation power control with path-loss compensation factor α_{FPC}. Power control is assumed to be done *after* resource allocation and mode selection [6].

Seven operating modes are considered in our simulations. 2-TS NWC and 4-TS scheme are cases when all UE pairs are forced to communicate using 2-TS NWC and 4-TS (cellular) transmission schemes respectively.

TABLE I
SIMULATION PARAMETERS

System bandwidth	5 MHz
Carrier frequency	2 GHz
Gain at 1 m distance	-37 dB
Path loss coefficient	3.5
Log normal shadow fading σ	6 dB
Number of Monte Carlo iterations	100
Number of cells	7
Number of UE pairs per cell	4 (low traffic), 8 (high traffic)
Number of radio resources per cell	8
Cell radius	500 m
eNB transmit power	40 dBm
Path-loss compensation (α_{FPC})	0.8
Assumed constant UE power for mode selection (P)	-10 dBm (MS-NWC 1), 20 dBm (MS-NWC 2)

TABLE II
MODE SELECTION OUTPUTS IN LOW AND HIGH TRAFFIC SCENARIOS

Mode selection	**Low traffic**	**High traffic**
MS-NWC 1 (SINR maximizing)	D2D mode: 19 % 4-TS : 81 %	D2D mode: 28 % 2-TS NWC: 14 % 4-TS : 58 %
MS-NWC 2 (Spectrum efficiency maximizing)	D2D mode: 19 % 2-TS NWC: 81 %	D2D mode: 21 % 2-TS NWC: 72 % 4-TS : 6 %
MS without NWC	D2D mode: 19 % Cellular: 81 %	D2D mode: 20 % Cellular: 80 %

The next two modes (MS-NWC 1 and MS-NWC 2) assume that it is possible to choose any of the transmission schemes in Figure 2, i.e. using D2D-NWC-cellular mode selection. MS-NWC 1 represents end-to-end SINR-maximizing mode selection while MS-NWC 2 represents spectral efficiency-maximizing mode selection.

The last mode, MS without NWC, is a mode selection strategy where it is possible to choose either D2D or cellular (4-TS mode). Network coding is not supported. The selection is based on simple channel gain comparison, i.e. if the channel between transmitting UE and the receiving UE is better than the channel between transmitting UE and the eNB, D2D mode is selected. Otherwise, cellular mode is selected.

B. Analysis

1) Behaviour of the Mode Selection Algorithm: Table II shows the transmission modes selected by the mode selection algorithm in two different traffic scenarios. We can observe that the SINR-maximizing mode selection tends to choose a transmission scheme that consumes more resources in an attempt to reduce interference, while spectral-efficiency maximizing mode selection chooses recourse-efficient modes (2-TS NWC or D2D mode) most of the time.

2) End-to-End SINR: Figure 4 compares the SINR performance of the transmission schemes of Figure 2, along with MS algorithms in a cellular network that supports both NWC and D2D (MS-NWC 1 and MS-NWC 2) and MS in an integrated D2D-cellular network (MS without NWC). The SINR is maximized with proper MS (MS-NWC 1) and the gain

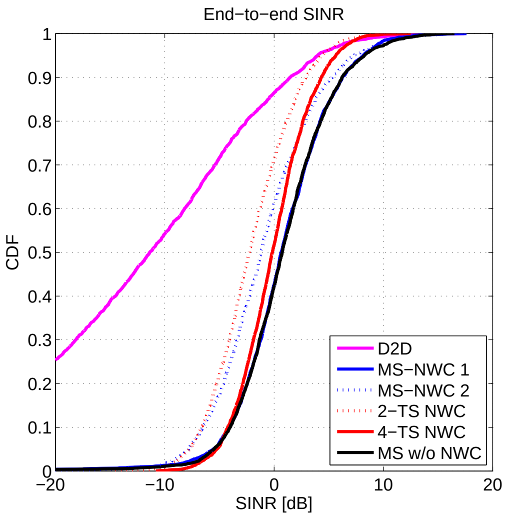

Fig. 4. End-to-end SINR performance of the transmission schemes under study, low traffic scenario (4 UE pairs per cell), including the D2D (direct) mode, the 2 and 4 TS schemes and the various mode selection schemes.

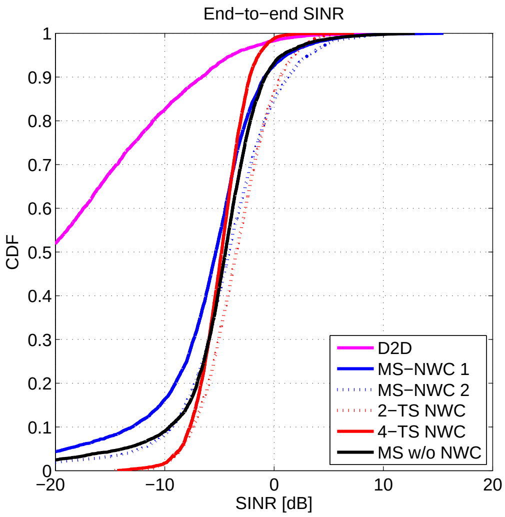

Fig. 5. End-to-end SINR performance of the transmission schemes under study, high traffic scenario (8 UE pairs per cell).

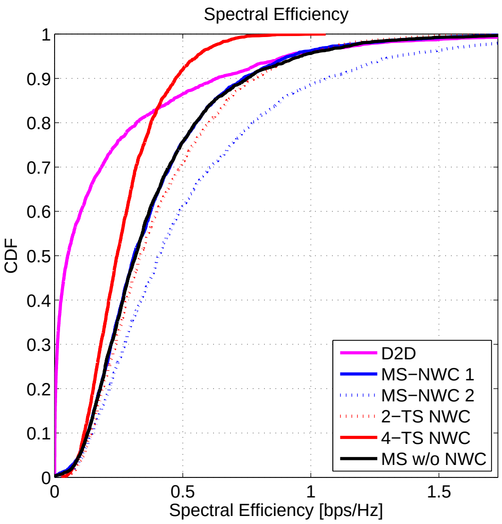

Fig. 6. Spectral efficiency of the transmission schemes under study, low traffic scenario (4 UE pairs per cell).

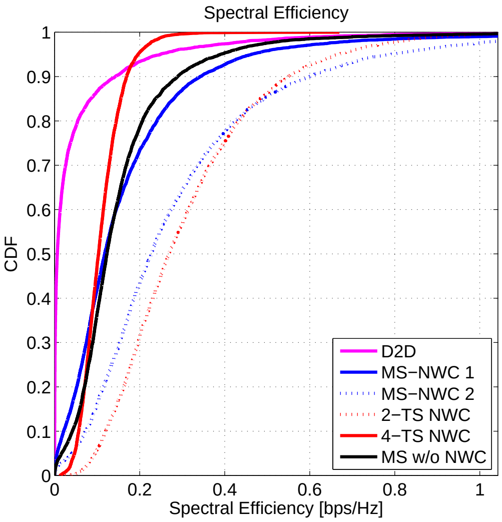

Fig. 7. Spectral efficiency of the transmission schemes under study, high traffic scenario (8 UE pairs per cell).

of employing NWC in an integrated cellular and D2D network in terms of SINR is negligible.

However, as shown in 5, MS-NWC 1 performs badly when the interference level is high. This is caused by inaccurate SINR prediction resulted from assuming constant power for all UEs. In high traffic situation, it is better to employ MS-NWC 2 because the inaccuracy of SINR prediction is suppressed by logarithmic function in the mode selection criterion. In any case, Figure 4 and Figure 5 prove that an integrated D2D-NWC-cellular network can always achieve high end-to-end SINR with a proper mode selection.

3) Spectrum Efficiency: As Figure 6 shows, however, NWC can lead to significant spectral efficiency increase if proper mode selection is employed; for example, MS-NWC 2. This shows that spectral efficiency is the main benefit of introducing NWC into an integrated D2D-cellular network. MS-NWC 2 also outperforms other mode selection strategies in high traffic scenario as shown in Figure 7.

4) Invested Transmit Power: Furthermore, as indicated by Figure 8, the high spectral efficiency of MS-NWC 2 can be realized at low power consumption. In other words, a network that supports both D2D and NWC is more energy-efficient than a network that supports only NWC. This is the gain that D2D brings in a cellular network employing NWC.

VI. CONCLUSION

In this paper, we have raised the question of how D2D and NWC technologies can be integrated in cellular networks in scenarios in which local (proximate) communication opportunities exist. We have shown that introducing NWC in integrated D2D-cellular networks can provide significant spectral efficiency gain. On the other hand, introducing D2D in a cellular network employing NWC reduces the invested

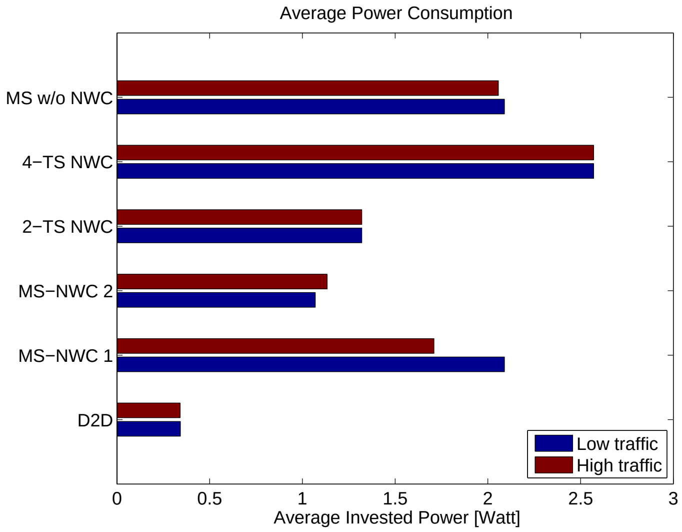

Fig. 8. Average power consumption of the transmission schemes under study.

transmit power. Our investigations suggest that D2D and NWC can complement one another and be friends provided a proper mode selection algorithm is applied by the network.

APPENDIX: DETAILED SINR ANALYSIS

A. Two-Time Slot (2-TS) Network Coding

The signal received at the relay in the first time slot is expressed as follows.

$$r = \sqrt{P_A} h_U x_A + \sqrt{P_B} g_U x_B + \left(\sum_k \sqrt{P_{I_k}^{(1)}} i_{R_k}^{(1)} x_{i_k}^{(1)} \right) + n_R \quad (6)$$

After receiving signals from both sources, the relay transmit its network coded signals to sources A and B. The signal received at source A in the second time slot is expressed as follows.

$$y_A = G \sqrt{P_R} h_D r + \left(\sum_k \sqrt{P_{I_k}^{(2)}} i_{A_k}^{(2)} x_{i_k}^{(2)} \right) + n_A \quad (7)$$

We assume that h_U and h_D are known to source A, g_U and g_D are known to source B, while G and P_R are known to both sources. Each source also knows its own data symbols. As a consequence, interference terms whose components are known to the receiver can be excluded in the SINR calculation. Substituting (6) into (7) gives

$$\begin{aligned} y_A \;=\;& \underbrace{G\sqrt{P_R} h_D \sqrt{P_A} h_U x_A}_{\text{known by source A}} + \underbrace{G\sqrt{P_R} h_D \sqrt{P_B} g_U x_B}_{\text{desired signal}} \\ & + G\sqrt{P_R} h_D \left(\sum_k \sqrt{P_{I_k}^{(1)}} i_{R_k}^{(1)} x_{i_k}^{(1)} \right) + \\ & G\sqrt{P_R} h_D n_R + \left(\sum_k \sqrt{P_{I_k}^{(2)}} i_{A_k}^{(2)} x_{i_k}^{(2)} \right) + n_A \end{aligned}$$

Taking the ratio of desired signal's power over interference and noise power, while excluding the known signals from the interference, the end-to-end SINR at source A is written according to (1) and (2).

B. Four-Time Slot (4-TS) Scheme

The first and second time slots are allocated for communication from source A to source B. In the first time slot, source A transmits x_A to the relay, and the relay received r_A. In the second time slot, the relay amplifies r_A by gain G_B and transmits to source B. The third and fourth time slots are allocated for communication from source B to source A. In the third time slot, source B transmits x_B to the relay, and the relay received r_B.

$$r_B = \sqrt{P_B} g_U x_B + \left(\sum_k \sqrt{P_{I_k}^{(3)}} i_{R_k}^{(3)} x_{i_k}^{(3)} \right) + n_R^{(3)}.$$

In the fourth time slot, the relay amplifies r_B by gain G_A and transmits to source A. The received signal at source A is expressed as follows.

$$y_A = G_A \sqrt{P_R} h_D r_B + \left(\sum_k \sqrt{P_{I_k}^{(4)}} i_{A_k}^{(4)} x_{i_k}^{(4)} \right) + n_A.$$

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